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Strengthening the resilience of small-scale fisheries: a modeling approach to explore the use of in-shore pelagic resources in Melanesia

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Abstract

Small-scale fisheries play a critical role in both poverty alleviation and food security. A large proportion of the world fish stocks are, however, getting fully or over-exploited. In this article we address these issues in the context of the small-scale fisheries of the Solomon Islands. The paper explores the extent to which in-shore Fish Aggregating Devices (FADs) can help increasing the resilience of the small scale fishery system and reconciling social, economic and ecological priorities. Based on the concept of 'time of crisis' developed recently in the viability literature, we propose to calculate a resilience index through a dynamic stochastic model calibrated by ethnological observations. The resilience index calculation reveals two major findings : (i) the resilience of the small scale fishery system is currently nonexistent and (ii) the introduction of FADs can improve it. The effects of the FADs' implementation are then discussed in the light of a socio-economic perspective. Such results bring new insights into the question of the future of the small scale fishery sector, especially in relation to the local economy evolution from a barter dominance to a cash oriented economy. At the same time, the current subsistence fisheries seems more resilient in general due to a distributive effects which ease the 'race for fish behaviors'. Finally, our analysis reveals that while the FADs implementation stands as a short and mid-term answer, demographic drivers are important and other alternatives will need to be considered if the overall viability of the system is to be maintained in the longer-term.

Key Words: Small Scale Fishery ; Resilience ; Environmental development ; Technological innovation ; data-poor situation

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1 Introduction

The sustainable exploitation of ecosystems and the conservation of biodiversity are two of the growing challenges of this century, along with the global eradication of poverty (Hall et al., 2013). Fishery, as a typical system based on the exploitation of renewable resources, is very illustrative of such a challenge. Three quarters of the world fish stocks are estimated to be fully or over-exploited (Garcia and Grainger, 2005; FAO, 2012), and 95% of the people depending on these fisheries are small-scale operators living close or sometimes below the poverty line in low and middle income countries (Heck et al., 2007; Béné et al., 2007; Mills et al., 2011). Although poverty in small-scale fishing communities is not explained only by the status of the resources (Yari, 2003/04; Béné and Friend, 2011), the link between resources and fishers' well-being is important.

Fisheries are also recognized to be a critical source of "rich food for the poor" (Kawarazuka and Béné, 2010; Béné et al., 2007; Allison, 2011). Both producers (small-scale fishers) and poor consumers in rural and increasingly in urban areas, depend on fish as a critical source of animal protein, micro-nutrient, vitamins and beneficial fats (Kawarazuka and Béné, 2010; High Level Panel of Experts, 2014). In this context, improving management of the world's fish stocks in such a way that available resources can better contribute to both poverty reduction and food and nutritional security in a sustainable manner is a priority (Andrew et al., 2007; Allison, 2011). Food security, poverty alleviation and resource conservation should therefore be the three main and inter-related objectives of fisheries management in the developing world. Yet identifying strategies which promote these three objectives remains challenging. This challenge is in many places further compounded by factors such as encroachment of markets, rapid population growth, increased demand for fish, and environmental change and degradation (High Level Panel of Experts, 2014).

Our objective is to explore these issues of inter-connection between natural resource conservation and development in the case of fisheries; and we propose to use the small-scale fisheries in the Solomon Islands as our main 'ground level laboratory'. For Solomon Islands' communities, marine resources constitute a unique and critical pool of available high-quality protein and an important source of household cash. However, like many countries in the Pacific region, coral reefs around Solomon Islands exhibit many signs of localized depletion of finfish stocks (Green et al., 2006; Brewer et al., 2009). A critical question therefore is: to what extent and under which conditions can these marine resources continue to fulfil their socio-economic functions (cash, livelihood and food provision), and at the same time be exploited in a manner that does not threaten their current or future ecological capacity? To address this question we developed a novel approach where we combine elements of viability theory with aspect of resilience, and use a bio-economic model designed and calibrated with local data to explore the system dynamics.

Viability (or viable control) approach (Aubin, 2009) is a dynamic system-based approach that has now been recognized as an insightful modelling framework in relation to natural resource management (Cury et al., 2005; Eisenack et al., 2006; Doyen and DeLara, 2010), especially in fisheries -see, e.g., Béné et al. (2001); Doyen and Béné (2003); Martinet and Doyen (2007); Bene and Doyen (2008). Under this viability approach the objective is not to identify optimal or steady state paths for the co-dynamics of resources and their exploitation, but rather to identify desirable combinations of states and associated controls that keep the system's viability conditions satisfied [1]. In our Solomon Islands' case-study, these viability conditions relate to marine resource conservation, food security and poverty alleviation. When considered together, these constraints delimit a multi-dimensional space called the 'viability domain'. In this specific context the aim of the viability approach will be to analyse the compatibility between the dynamics of that system and the state constraints, and to determine the set of controls (or decisions) that will maintain the system's trajectories within this viability domain.

The concept of resilience will then be used to further explore the behaviour of the system around the boundaries of this viability domain. Many definitions of resilience have been proposed in different disciplines -see Manyena (2006); Bahadur et al. (2010) for reviews of these definitions. Most definitions share in common the basic idea that a resilient system is able to continue functioning effectively even after a shock. Quantifying or measuring this ability is however methodologically difficult (Armitage et al., 2012; Frankenberger and Nelson, 2013; Béné et al., 2012). In our case, we follow Béné et al. (2001) and Martin (2005) who, in a dynamic context, propose to link resilience to the concept of 'time of crisis'. The 'time of crisis' is the time it takes for a dynamic system to come back into its viability domain, following a shock. The more resilient a system is, the shorter the time of crisis will be. This approach is in fact relatively close to some of the earlier 'engineering' definitions of resilience as proposed by, e.g. Holling (1973) who defined resilience as the "ability of a system to bounce back or return to equilibrium following disturbance". In our case these disturbances will be considered by introducing stochastic elements in both the ecological and human dynamics of the system. The true novelty of the approach, however, comes from the fact that so far (to the best of our knowledge) linking viability to resilience and using the mathematical concept of time of crisis as a way to quantify the system's resilience in an

1. From an ecological viewpoint, the so-called population viability analysis (PVA) (Morris and Doak, 2002) is remarkably close to this viability approach as it focuses on extinction probability in an uncertain (stochastic) environment. The Tolerable Windows Approach (TWA) proposes a similar framework on climatic change issues (Bruckner et al., 1999).

empirical case-study has never been tried [2].

2 The Solomon Islands' small scale fishery

The Solomon Islands' archipelago presents ecological and socio-economical characteristics that are relatively illustrative of the Melanesian context. On an ecological perspective, the Solomon Islands are situated within the Coral Triangle (see Fig. 6) and as such display one of the highest levels of marine bio-diversity in the world, with astonishing levels of primary productivity. The local artisanal fishers exploit diverse coral reef and pelagic species. The principal families amongst the reef resources include Serranidae (sea basses and groupers), Lutjanidae (snappers), Lethrinidae (emperors), Acanthuridae (surgeonfishes, tangs, unicornfishes) and Scaridae (parrotfishes). The pelagic catches are dominated by the skipjack tuna (*Katsuwonus pelamis*). Once landed, reef and pelagic fish are either consumed by fishers and their families, or sold locally (Sulu et al., 2000). Other exploited products include sea-cucumber, trochus, and shark fins. Those, however, will not be considered in this paper as their influence on the system is minimal at the present time: the shark fin market has not (yet) fully developed in Solomon Islands (compared to other places in the Pacific), the sea-cucumber fishery has been closed since 2005 due to strong evidence of overfishing (Ramofafia, 2004) and the trochus fishery has never really recovered from overexploitation 200 years ago and represents only a negligible part of landings and fisher cash (Foale, 1998, 2008). Our work will therefore focus on the reef fish and skipjack tuna resources.

From a livelihood perspective, households in Solomon Islands engage in fishing for two main reasons; subsistence (self-consumption of fish to complement the home garden and contribute directly to food security) and cash-income to purchase other commodities: foods (e.g. rice) and essential goods (clothes, pieces of furniture, kitchen utensils, etc.), (Kile, 2000). In fact the country is characterized by one of the highest fish consumption rates of the region (35 kg/person/year (Bell et al., 2009)), but also the highest demographic growth rate in the Pacific region (between 2.3 and 2.8% (CIA, 2001)) and the lowest Human Development Index of the region (143/186). In those circumstances, the small-scale fishery represents the only economic opportunity for many (rural) households and stands as a keystone sector.

In Solomon Islands all fishers -essentially male head of rural households- are engaged in reef fishing, and to a lesser extent outside the reef in inshore sea fishing. These fishers split their fishing time (around 15 hours per week) between the two fisheries (Aswani, 2002,

2. The work of Duer-Balkind et al. (2013) addresses the conciliation between sociological drivers and ecological drivers under a quantitative approach of resilience. Although they do not take into account the economical constraints that drives the fishing efforts. Such economical constraints can be actually considered through the socio-economic viability constraints.

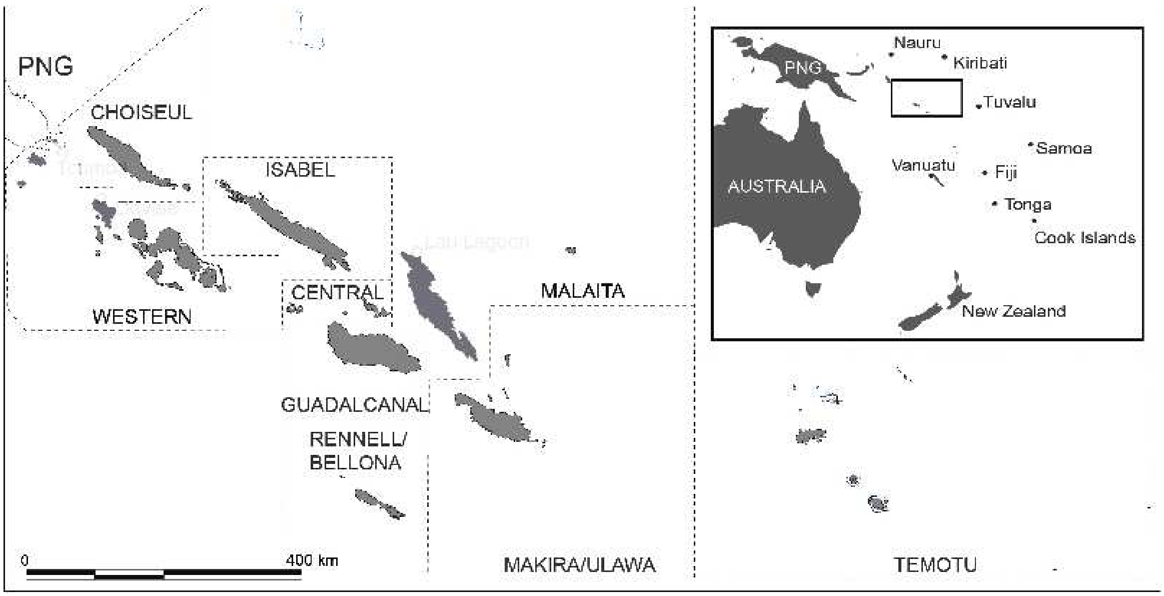


Figure 1: Map of Solomon Islands

1998), but with a marked preference for the reef fishery. The limited number of outboard engines and their relatively high operating costs also reduce considerably the number of local fishers who can access the tuna resource on a regular basis. As a result, a typical fisher would be mainly involved in coral reef fishery, with approximately only 10 % of his fishing time spent outside the reef targeting the tuna resource (Aswani, 2002, 1998). The two types of resources, coral and pelagic, imply different fishing techniques so we distinguish two fleets; the reef fleet which restricts its operation to reef areas (fishers using dugout canoes or fiberglass boats without outboard motors); and the tuna fleet, which operates outside the reef (dugout canoes without outboard motors and a few fiberglass boats with outboard motors). In these conditions, the development of small-scale inshore moored FADs which would attract pelagic tuna closer to the reef and make this resource more accessible to small-scale fishers is considered as one possible option to increase the fisheries system's productivity (Bell et al., 2009, 2015). In other parts of the Pacific region for instance a growing number of inshore FADs are currently being tested (Désurmont and Chapman, 2000; Prange, 2009). Yet, at the time of the study, inshore FADs were still not widely used by the small-scale fisheries in the Solomon Islands (Prange, 2009) -despite a growing interest in their use (pers comm.).

In this context, the objective of this research was to explore further this FAD option and to determine in particular the extent to which in-shore FADs could increase the resilience of the fisheries system. For this the study was designed to compare two scenarios, relying on our bio-economic model: one scenario with in-shore FADs and one without. The main effect of introducing FADs in the fishery is assumed to be an increase in the catchability [3] of the tuna resource. A SPC report (Langley and Hampton, 2008) reports for instance a 3-fold increase in tuna catchability from 1982 to 2006, during a period when a substantial number of new FAD were deployed within the national seas. In another FAD study Albert et al. (2014) also observes substantial increases in catchability of pelagic fish around off-shore and in-shore FADs.

3 Method

3.1 A bio-economic model

Our bio-economic model is purposely simple in order to make the results analytically trackable. The resource dynamic of the model is based on a Lotka Volterra function (Volterra and Brelot, 1931) determined by two main sets of biological parameters; (i) the intrinsic growth rate r_i of the groups of species included in the model and (ii) the matrix $S_{i,j}$ that captures the trophic relationship between groups i and j (positive if j is a prey of group i, negative if j is a predator of group i, and nil if there is no interaction) with both i and $j \in \{1, 2, 3\}$. The two sets of parameters are assumed to be homogeneous across the whole Solomon Islands' archipelago and its surrounding region. In addition the model accounts for the differential impacts of the fishing efforts $e_k(t)$ imposed by the two fleets (where k=1 for the coral reef fishery and k=2 for the off-shore tuna fishery) through catchability parameters $q_{i,k}$. A fleet refers to a gear specification; one fisher is part of the two fleets using two combinations of gears, mainly drop line and spear gun above the reef and in the lagoon and different types of trolling lines outside the reef. Thus, the biomass $B_i(t+1)$ of group i at time $t+1$ depends on previous stocks' biomass level $B_i(t)$, trophic interactions with other groups through $S_{i,j}$, the impact of the fishing efforts $e_k(t)$ and the number of fishers $l_k(t)$ engaged in the fleet k (fixed all along the simulation), through the dynamic relation 1.

$$B_i(t+1) = B_i(t) \cdot \left(1 + r_i(t) - \sum_{j=1}^{3} S_{i,j} \cdot B_j(t) - \sum_{k=1}^{2} q_{i,k}(t) \cdot e_k(t) \cdot l_k(t)\right) \tag{1}$$

Although we restrict our analysis to include only reef and pelagic fish resources, the full range of interactions among these groups remains complex and largely unknown. Here we model a simplified system focusing only on the most important interactions. In the data-poor context that characterizes most developing countries (including the Solomon Islands),

3. Catchability is the proportion of the stock that is removed by 1 unit of fishing effort over 1 unit of time

the most ecologically robust assumption is to categorize prey and predator species into separate groups in an attempt to capture the main heterogeneity and diet dynamics of the species considered (Larkin and Gazby, 1982). The Solomon Islands' reef fish resources were therefore split into two groups; (i) piscivors (essentially the Serranidae family [4]) and (ii) herbivors (Lutjanidae, Lethrinidae, Acanthuridae and Scaridae). In the rest of the article, the piscivors are considered as predators and herbivors as prey. Skipjack tuna were considered a third separated group since this species does not interact directly with reef fish (Fernandez and Allain, 2011; Buckley and Miller, 1994).

The fishing efforts $e_k(t)$ are expressed in hours/fisher, the catchability $q_{i,k}$ in 1/hours, and the biomass $B_i(t)$ in kg/m^2. We assume that the intrinsic growth rate r_i and catchability $q_{i,k}$ are subject to stochastic fluctuations following two independent uniform laws $\mathcal{U}_r$ and $\mathcal{U}_q$. All parameters and initial conditions are listed in Table 3 in Appendix.

Using a standard Schaefer production function (Schaefer, 1957), the catch $H(t)$ is estimated by:

$$H(t) = \sum_{i=1}^{3} \sum_{k=1}^{2} B_i(t) \cdot q_{i,k} \cdot e_k(t) \cdot l_k(t) \cdot \text{area}_k \tag{2}$$

with area$_k$ corresponding to the national fishing area (Spalding et al., 2001) (see Table (3) in Appendix). The catch is then used for two purposes, the subsistence (quantity of fish for direct consumption) and cash (value of the remaining fish sold on local or regional markets). The allocation between the subsistence and the cash is determined by the parameter α. The individual households' subsistence is therefore:

$$Sub(t) = \sum_k \alpha_k \sum_i \frac{H_{i,k}(t)}{l_k(t)} \tag{3}$$

while the individual cash is:

$$Cash(t) = \sum_k (1 - \alpha_k) \cdot \sum_i p_i(t) \cdot \frac{H_{i,k}(t)}{l_k(t)} - c(t) \cdot \sum e_k(t) \tag{4}$$

where p_i(t) is fish local market prices and $c(t)$ stands the mean cost of effort. Both price and cost vary during the simulation according to the inflation $p(t) = p(t_0) \cdot Infl^t$ and $c(t) = c(t_0) \cdot Infl^t$ with Infl being the month inflation coefficient.

Time unit for the model was month and and the simulation was run over a period of 15

4. Serranidae family accounts for the highest trophic level on the coral reef system. In this family we will focus on the medium size individuals since the number of big individuals have been reduced by the fishing activity.

years (i.e. $t_0 = 2011$ and $t_f = 2026$). Each simulation was based on thousand trajectories. For each trajectory, the biomass of each group was computed using equation 1 and the stochastic functions 5.

3.2 Calibration

Our bio-economic model relies on data collected during six months of fieldwork (March to August, 2011) complemented by existing secondary anthropological studies (Aswani et al., 2007; Aswani, 2006; Sabetian and Foale, 2006) and two biological databases (Langley and Hampton, 2008; Green et al., 2006). Details of the different steps followed to construct such a model in a data-poor situation are provided in Figure 6 in the Appendix. The socio-economical parameters reflect the 2011 context, while the latest skipjack tuna biomass estimation was made in 2006 (Langley and Hampton, 2008) and the coral reef fishes assessment in 2004 (Green et al., 2006). The fieldwork in 2011 within four communities (Ove, Maleai, Gou'Ulu, Lilihina) in various places of the country, however, has brought some question-marks about the validity of the stock assessments. The biomass might be 20% lower in 2011 compared to 2004 levels. Therefore a combination of different initial conditions $B_i(t_0)$ was used for the three groups (reef fish; prey and predators; and tuna) with lower and higher ranges of resources considered in the range [0 ; 2] of the 2004 and 2006 levels (i.e. +/- 100%). Such high variation also does help to explore more comprehensively the dynamic of the system.

The intrinsic growth r_i and the trophic matrix $S_{i,j}$ are calibrated in accordance with previous studies. For the first two groups (reef predator and reef prey), the trophic matrix were derived from Doyen et al. (2007) whose approach[5] was based on group' equilibrium biomass B_i^{eq}. The equilibrium biomass B_i^{eq} was assumed to occur when stocks have reached their relative carring capacity, estimated to be $2 * B_i(2004)$ (Green et al., 2006) assuming that no fishery operate. When the biomass are constant with no capture the expression (1) becomes $r_i(t) = \sum_{j=1}^{3} S_{i,j} \cdot B_j^{eq}(t)$, which helps to compute the $r_i(t)$ once the $S_{i,j}$ are known. For the skipjack the values are derived from Hardy et al. (2013), while the others ($S_{1,3}$,$S_{2,3}$,$S_{3,1}$,$S_{3,2}$) are set to zero (no trophic interaction between tuna and reef fishes).

The calibration of the uniform law $\mathcal{U}_r$ relates to the maximum variation range which results in a 20% annual fluctuation of the Serranidae biomass. This is in line with Sabetian's estimation of the natural annual fluctuation (Sabetian, 2003). In the absence of

5. The terms S_i, j have been calculated using the stomach content of the predators through the method of Doyen et al. (2007) with diets Vol_i taken from the FishBase database (Serranidae average diet with 30% to 40% of fish for medium size individuals), weights W_i equal to the biomass $B_i(2004)$ divided by the densities $D_i(2004)$ (Green et al., 2006) (see Table (3) in Appendix) and groups' equilibrium biomass B_i^{eq}

more information, we assumed a similar level of fluctuation for the other groups and tested different intrinsic growth levels with variation ranges from [-10%,10%] to [-100%,100%] [6]. We introduced therefore a random law $\mathcal{U}_r(-0.8, +0.8)$ to the model, whereby a random r value is drawn from an uniform distribution within the interval of -0.8 to +0.8. In addition to these ecologically-driven fluctuations, we assume that the catchability parameters $q_{i,k}$ also fluctuate stochastically. In this case, the amplitude was arbitrarily set at $\mathcal{U}_q(-0.2, +0.2)$. Introducing this medium level of fluctuation was justified also in the case of the skipjack tuna stock, as this species is highly mobile and capable of migrating from Papua New Guinea to the north of Australia (Lehodey et al., 2003), inducing fluctuation in the availability of the stock at the local level. We therefore have the following stochastic conditions for the biomass growth rate and the catchability:

$$r_i(t) \rightsquigarrow \bar{r}_i * (1 + \mathcal{U}_r(-0.8, +0.8)) \quad \text{and} \qquad q_{i,k}(t) \rightsquigarrow \bar{q}_{i,k} * (1 + \mathcal{U}_q(-0.2, +0.2)) \tag{5}$$

The rest of the parameters have been calibrated using the field work data of the four communities of Ove, Maleai, Gou'Ulu and Lilihina together with the information derived from the existing literature. Each of these communities are very distinguishable in terms of fishing and consumption habits although some common features are identifiable such as the way the catch is used. In those communities fish is shared with other members of the extended family including other fishers' households. This redistribution process is expected to provide the necessary amount of fish to satisfy protein needs for all. Wild fish remains the most accessible and the cheapest source of animal protein -the canned tuna is four time more expensive (per kg) and chicken and eggs are not so available in remote villages. The household cash also depends heavily on the fishing activity through regular selling in local markets as the economic alternatives are very rare in those rural areas. Overall this means that both levels of subsistence and cash are closely linked to the level of fishing activity. Schwarz et al. (2007) estimates that in the case of rural population approximately 60% of the catch is home-consumed, and the remaining 40% is sold. We therefore use the parameter $\alpha = 0.6$ to represent fish self-consumption and $1 - \alpha = 0.4$ for fish sold for cash. The subsistence is thus more important although some more cash-oriented behaviors are emerging progressively and the subsistence allocation is expected to have decreased. In this context the α might continue to evolve in the near future and we have taken this eventuality into account: different α are tested from a strong subsistence based economy with $\alpha = 0.8$ to a strong cash based economy with $\alpha = 0.2$.

6. In fact, a high variation range of [-80%,80%] is necessary to reach a 20% annual biomass variation when no fishing occurs ($e_1 = 0$).

The linear cost c included in the cash expression account for the average operating costs. The latter is estimated to be around 2.5$SB per hour per fisher ($SB = Solomon dollar) for the majority of fishers operating with dugout canoes rather than outboard motors (Kronen, 2007). The fish price was calibrated by taking the average price between rural and urban markets (since fishers sell to both) for the three main fish groups as follows: 5.5 SBD/kg for piscivors, 4.5 SBD/kg for herbivors and 5 SBD/kg for skypjack tuna. The three main national market were also assessed through a 4 weeks observation, asking cost and price to fishers/resellers in the market of Honiara (one week), Auki (one week) and Gizo (two weeks) which have given equivalent figures. The inflation impacting the cost and the price are fixed according to the report on international inflation which estimated an inflation level $Infl = 1.0083$ on a month basis (Dept, 2014).

A maximum fishing effort of 90 hours/month was introduced to reflect the maximum number of hours each fisher can engage in fishing activities per month, while still contributing to other important social and livelihood activities (family, gardening, social interactions, etc.). This limitation is in line with figures proposed by Albert et al. (2014). On the other hand, fishing effort is never equal to zero because of residual or illegal fishing happening even during temporary or permanent fishery closures. We assume that this residual fishing effort is a minimum of 2 hours/month/fisher. This means that the condition:

$$2 \leq \sum_{k=1}^{2} e_k(t) \leq 90 \tag{6}$$

defines the overall fishing time for each fisher. The catchability coefficients are derived from the work of Hardy et al. (2013), and are in agreement with fieldwork observation. Fieldwork observation consisted in the estimation of the fish catch on sporadic time spent on the landing sites waiting for fishers to come back as well as records during fishing trips conducted by the main author. As mentioned above the effect of the offshore FADs on the tuna catchability of industrial fleets is assumed to lead to a 3-fold increase (Hardy, 2014). We suppose this value to be effective for the small scale fishers at 10 miles from the shore, i.e. the maximum distance to the coast in terms of accessibility.

3.3 The resilience index

The resilience index is inspired by the work of Béné et al. (2001) derived from the concept of 'time of crisis' introduced by Doyen and Saint-Pierre (1997), and further adopted by Martin (2005) and Deffuant and Gilbert (2011). The basic idea behind the concept of time of crisis is to measure the time it takes for a dynamic system to come back into its viability domain, after at least one of its viability constraints has been violated.

Viability constraints We needed first to identify the viability constraints that delimit the viability domain. In our case these viability constraints were defined by three thresholds: (i) the ecological threshold with minimum biomasses above which the stocks have to been maintained to ensure the renewability of the resource; (ii) the food security threshold with a minimum fish catch that ensures individual household' food security; and (iii) the cash poverty line threshold with a minimum cash level derived from fish sale that is necessary to maintain households above the cash-poverty line. When considered together, these three constraints delimit the system's viability domain within the space of the system's possible trajectories.

Ecological constraint The ecological constraint is linked to the minimum biomass level B_i^{lim} above which it is necessary to remain to secure the sustainability of the resource i. In our case, we arbitrarily set the B_i^{lim} at 30 % of the $B_i(2011)$ biomass. We suppose the stocks to be on average at 70% of their carrying capacities' levels (implying a diminution of the carring capacity level due to habitat degradation), the 30% of the current level implies a vulnerable level of 21% (0.3*0.7=0.21) of the carrying capacity level K_i, i.e. $B_i^{lim} = 0.21 \cdot K_i = 0.3 \cdot B_i(t)$. This figure is slightly above the 20% (or 80% reduction) of initial levels mentioned in the critically endangered criteria under the condition A.3. (Species Survival Commission, 2000). We have therefore the first viability constraint:

$$B_i(t) \geq B_i^{lim} = 0.3 \cdot B_i(0) \tag{7}$$

Food security constraint The second constraint relates to the the minimum fish consumption level Sub^{lim} necessary to ensure food security at the household level (HH). The FAO (1981) report recommends a weekly amount of protein of 0.8 g/kg, which is equivalent to 21 kg of fish for an average 70 kg person (60 kg for women and 80 kg for men) or 9.5 kg/household/month (based on the figure of 5.2 persons per household in Solomon Islands (National Statistic Office, 2008)). We assume that fresh fish is the cheapest protein favored by people close to the food insecurity threshold. We also assume in general that at least half of the fish is consumed, half is leftover [7] (bones, head, tail, intestines, scales and gills). The second viability constraint (which is slightly above the recommendations proposed by Bell et al. (2015)), is:

$$Sub(t) \geq Sub^{\mathrm{lim}} = 9.5 \text{ kg/hh/month} \tag{8}$$

7. This estimation corresponds to fieldwork observation.

Cash source constraint The third constraint of the system relates to the minimum cash level $Cash^{\lim}$ required to maintain people above the relative poverty line. The National Statistics Office and UNDP, Pacific Center (2008) indicate a weekly cost of 225 \$SB per households for the highest quintile, and a weekly basic need poverty line of 47 \$SB per household. This last figure is equivalent to 204 \$SB/hh/month. This condition induces a third viability constraint for the system, namely:

$$Cash(t) \geq Cash^{\lim} = 204 \text{ \$SB/hh/month} \tag{9}$$

Crisis function The simulation is based on 1000 trajectories associated to an initial condition $B_i(t_0)$. Amongst these 1000 trajectories, the model identifies every trajectory with either total or partial violation of the viable constraints (7), (8), or (9) and calculates the number of months during which these violations occur. The 'worst' trajectory $Cr(B_0, e(t))$ which is the trajectory with the longest time of crisis, is then identified using the following algorithm:

$$\begin{gathered} Cr(B_0, e(t)) = \max_{r,q} \; \sum_{t=t_0}^{t_f} \mathbf{1}_{\mathbb{C}}(B_0) \\ \text{with} \;\; \mathbf{1}_{\mathbb{C}}(B_0) = \begin{cases} 1 & \text{if constraints (7), (8) and (9) hold true} \\ 0 & \text{otherwise} \end{cases} \end{gathered} \tag{10}$$

For the 15-year simulations, fishing effort choices are made at the start of three 5-year distinctive decision periods. The 5 year period accounts for the adaption potential of the communities, it also illustrates the resilient potential after big event such as the ethnic tension in 2000 and the tsunami in 2007 (Schwarz et al., 2010). At the start of the first decision period (at t_0 equivalent to 2011), the choice of both fishing effort $e_1(t_0)$ and $e_2(t_0)$ is assumed to depend only on the information on the initial state $B_i(t_0)$. Using $e_1(t_0)$ and $e_2(t_0)$, we produce 10 trajectories corresponding to a 5-year simulation. Each trajectory relies on a 'non-anticipative' stochastic control (Shapiro et al., 2009). At the start of the second decision period (at t_1 equivalent to 2016), we have 10 new states of biomass $B_i(t_1)$. For each of these new states $B_i(t_1)$, fishing efforts are chosen for both $e_1(t_1)$ and $e_2(t_1)$. To continue the simulation to a 10-year period, we increase the stochasticity and compute 10 new trajectories for each $B_i(t_1)$. All the trajectories are generated through a stochastic procedure incorporating 10 new sets of monthly random variations derived from expression (5). We proceed in the same way to decide for both $e_1(t_2)$ and $e_2(t_2)$ for the third decision period (at t_2 equivalent to 2021). We obtain at the end 1000 trajectories equal to 10 different replicates of the first period times 10 different replicates of the second period times 10 different replicates of the third one. This method has been coded using the Scilab software.

The three fishing effort combinations $(e_1(t_0),\, e_2(t_0))$, $(e_1(t_1),\, e_2(t_1))$ and $(e_1(t_2),\, e_2(t_2))$ are chosen in the range defined in (6) and computed with a 8 hours incrementation (corresponding to a fishing trip) in such a way that they minimize the crisis function $Cr_g(B_0, e(t))$. The incrementation is first applied to the coral reef fishery effort and then to the tuna effort, so that the effort choice prioritizes the coral reef fishery, thus reflecting the current empirical reality. We then compute the minimum crisis function $Cr_g(B_0)$:

$$Cr_g(B_0) = \min_{e(.)} Cr(B_0, e(t)) \tag{11}$$

Once this minimum crisis function $Cr_g(B_0)$ is computed we can calculate the resilience index associated to B_0 using the inverse of the minimum crisis function, as follows:

$$R(B_0) = \frac{1}{1 + Cr_g(B_0)} \tag{12}$$

A fully resilient situation will be characterized by a resilience index $R(B_0)$ equal to 1 (i.e. with a time of crisis nil: $Cr_g(B_0) = 0$), while a resilience index $R(B_0)$ equal to 0 would indicate situations with no resilience at all, that is, with an infinite time of crisis. Intermediate situations where $0 < R(B_0) < 1$ correspond to cases where the system is able to return to its viability domain after a while [8].

4 Results

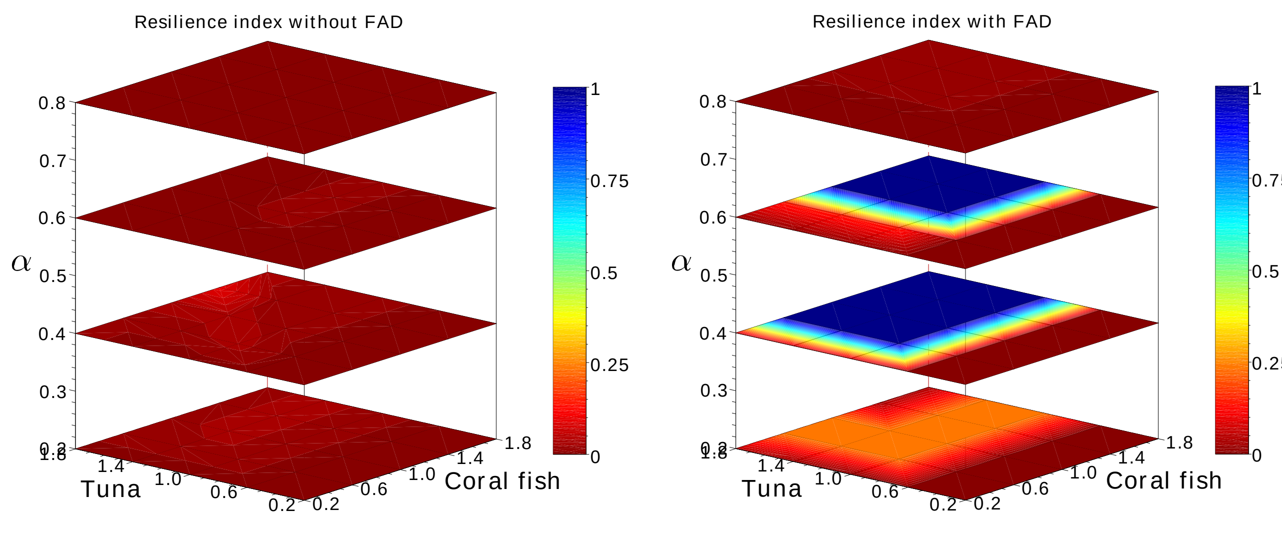
The resilience index $R(B_0)$ was computed for different combinations of initial parameters (coral reef fish biomass, tuna and α) within a range of multipliers varying from 0.2 to 2 for the biomass and from 0.2 to 0.8 for α. Fig.2(a) shows the result of these simulations in the case of non-FADs while Fig.2(b) shows the results with FADs. Blue areas indicate resilient state zones and dark red areas indicate non resilient state zones, with transition zone in orange-yellow. In addition, the detail of the 15-year simulation are presented in Fig.3 for non FADs scenarios and Fig.4 for FADs under referenced conditions (multipliers equal to 1.0 and $\alpha = 0.6$). The viable thresholds are depicted in green.

Global resilience The comparison of Fig.2b and Fig.2a shows clearly the positive effect of FADs on the resilience of the system: while the blue zone is absent in Fig.2a suggesting that even combinations corresponding to the highest levels of both reef and tuna resources

8. Note that intermediate situations can also occur in some very rare cases when the system does not have the time to return to its viability domain if the crisis occurs at the very last month of the simulation.

are not fully resilient without FADs, the introduction of in-shore FADs (Fig.2b) with $\alpha = 0.4$ and 0.6 creates a number of resilient combinations.

Within the FAD scenario, one further difference appears in relation to α. In particular the figure indicates that a lower α value (around 0.4) is associated with larger blue zone. This tends to indicate that in the presence of FAD, increasing the share of sold reef fish (i.e. diminishing the level of self-consumption from the current 0.6 to 0.4 ratio) would be an important driver of resilience improvement. Below 0.4 however the trend seems to reverse, with the resilience disappearing rapidly. The relation between resilience and α appears therefore to be non-linear.



(a) (b)

Figure 2: Representation of the Resilience index R(B0) through a color code where blue areas indicate resilience index equal to one (full resilience) and dark red areas indicate resilience index very close to zero (no resilience). The different indexes are computed for configuration without FADs (a) and with FADs (b) under different combination of coral reef fish initial biomass B1,2(t0) and skipjack tuna initial biomass B3(t0) with an amplitude from 0.2 (20%) to 2 (200%). The reference situation of Solomon Islands (S.I.) with amplitude 1 (100%) is indicated in the center. The parameter α is represented on the vertical axis (Z).

System trajectory evolution While Fig.2a and Fig.2b depict the overall outcomes in terms of resilience, they don't provide the detailed information concerning the system's 'internal' dynamics which leads to these different outcomes. The details of the different indicators (resource biomass, cash and subsistence levels) based on the 2011 values are depicted in

Fig.3 for the non-FADs and in Fig.4 for the FADs scenarios. All trajectories are depicted and show why the current situation without FADs is not resilient.

Starting with 2011 condition we can see that the coral reef sub-system is already low in terms of biomass. Fishing effort cannot be increased without risking any further degradation and so the coral reef fishing pressure is reduced to its minimum during the first 5-year period under both scenarios (with and without FADs). During the second period, the scenario with FADs indicates that fishers accessing the FADs do continue to fish at a minimum level within the lagoon while other fishers start to take advantage of the growing coral fish biomass generated during the first period (see Table 1). In contrast with no FADs option, the piscivors are continuously under pressure by fishers forced to stay around the reefs. The low quantity of resources is enough for the subsistence constraint to be satisfied but not sufficient to get enough fish to sell. The cash seems effectively to be the main constraining factor here.

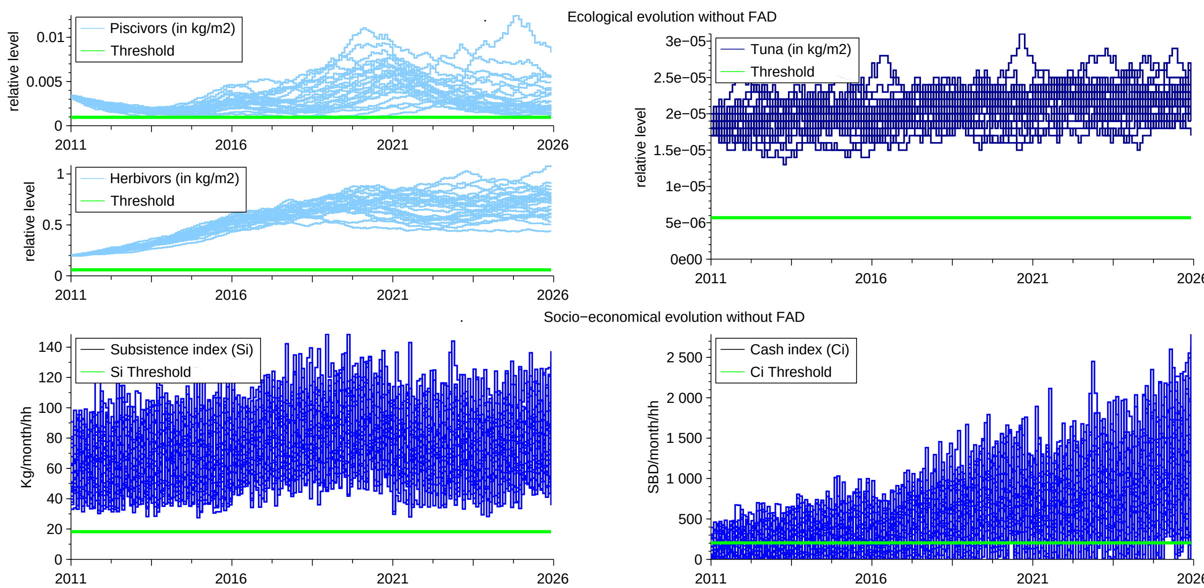


Figure 3: The detailed evolution of the system without FADs for coral reef fish biomass $B_{1,2}(t)$, skipjack tuna biomass $B_3(t)$ and the two socio-economical indicators, the subsistence index $Sub(t)$ (abbreviated Si) and the cash index $Cash(t)$ (abbreviated Ci), all possible trajectories are drawn (The first period of 5 years includes 10 trajectories, the second 100 trajectories and the third 1000 trajectories).

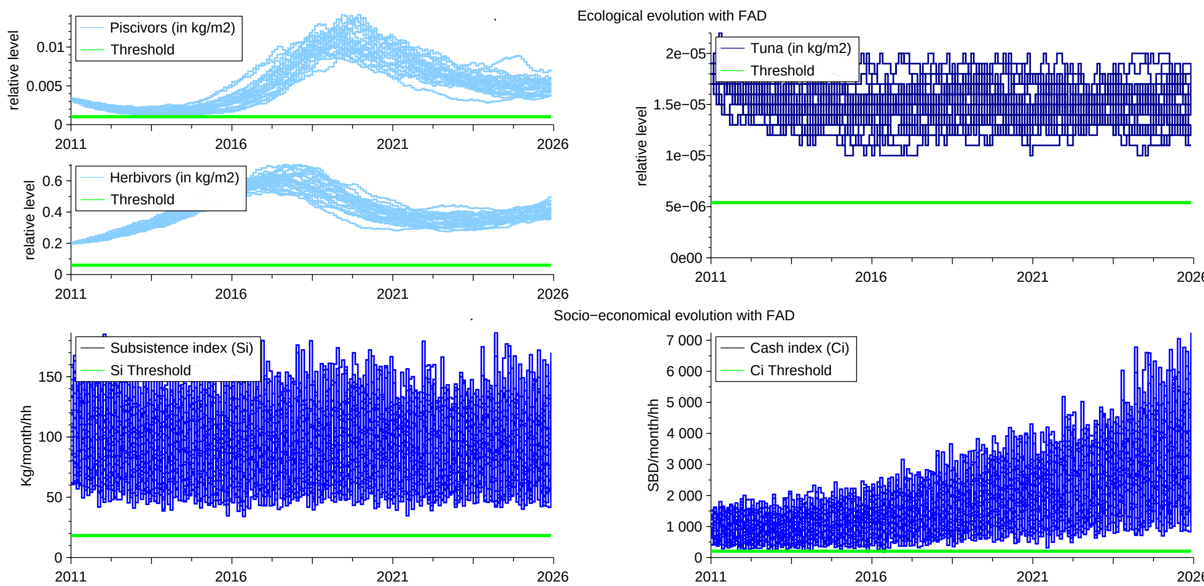


Figure 4: The detailed evolution detail of the system with FADs for coral reef fish biomass $B_{1,2}(t)$, skipjack tuna biomass $B_3(t)$ and the two socio-economical indicators, the subsistence index $Sub(t)$ (abbreviated Si) and the cash index $Cash(t)$ (abbreviated Ci), all possible trajectories are drawn (The first period of 5 years includes 10 trajectories, the second 100 trajectories and the third 1000 trajectories).

Condition	Fleet	First period	Second period	Third period
Without FADs	coral fish	2	26	34
	skipjack tuna	34	34	34
With FADs	coral fish	2	2	2
	skipjack tuna	18	18	18

Table 1: Effort detail in hours/fisher/month of scenarios depicted in Fig.2a and Fig.2b related to the current initial situation (2011). The efforts of the first period represent an average of the 10 combinations, the efforts of the second period represent an average of the 100 combinations, the efforts of the third period represent the average of the 1000 combinations

Provincial comparison The analysis presented above for the Solomon Islands archipelago as a whole can be disaggregated into provincial assessments by using the provinces' respective resources biomass estimates. While the tuna biomass is assumed to be exploited homogeneously among all provinces of the country [9], the values of provincial percentage of the coral reef fish biomass estimated by Green et al. (2006) are used to find the respective local abundance multipliers (table 2). The level of uncertainty of the initial coral ref fish is assumed to be the same however between the provincial and the national level.

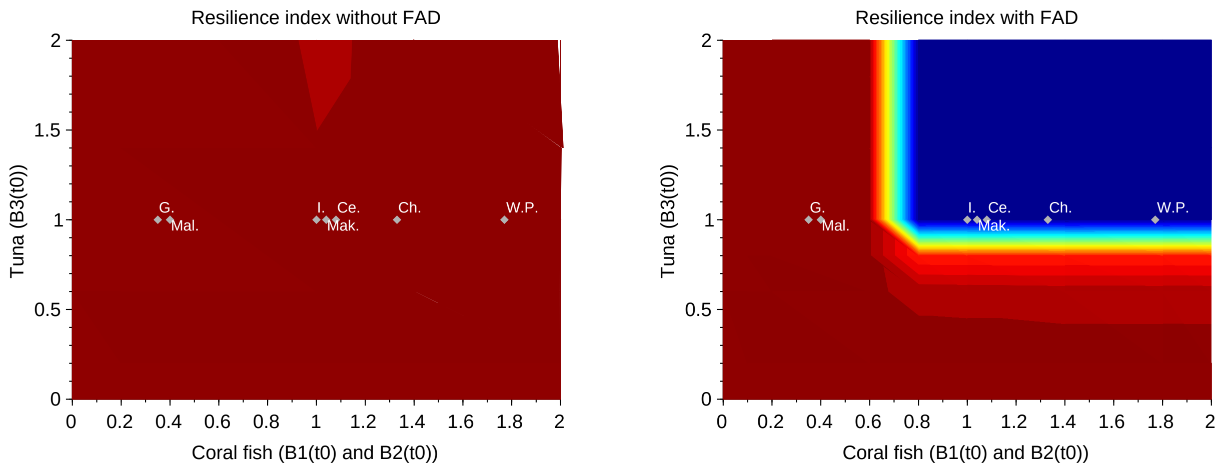
Region	Choiseul	Western P.	Isabel	Central	Gadalcanal	Malaita	Makira
coral fish	0.286	0.380	0.214	0.232	0.075	0.086	0.223
Multiplier	1.33	1.77	1.00	1.08	0.35	0.40	1.04

Table 2: Repartition of the national biomass by region, with average regional biomass in kg/m^2 and relative propotion to the national level

The results of the provincial analysis (with and without FADs) are shown on Fig.5 with the current α ($\alpha = 0.6$). Incidentally, Isabel province's situation corresponds exactly to the national situation in 2011 with a local multiplier of 1.0. The resource levels in the Central and Makira provinces are also relatively close to the national average and these provinces are therefore located close to the central point (1:1). The other provinces (Choisel and Western Province on the right-hand side; Guadalcanal and Malaita on the left-hand side) are located away from that central point with positions reflecting the reef fish resource status. Fig.5a indicates that without FADs, Choisel and Western Province exhibit no resilience, suggesting that the coral reef fish biomass of these two provinces would rapidly become unable to bear the high population pressure if no technical solution is proposed. The introduction of FADs (Fig.5b) in these two provinces 'boosts' their resilience as they get included in a dark blue zone.

In contrast, the Malaita and Guadalcanal small-scale fisheries remain no-resilient even after the introduction of FADs. The extension of the blue zone however strengthen the outcomes for the other provinces since the uncertainty of the initial coral reef biomass is largely taken into account.

9. The skipjack tuna assessment used for this analysis was conducted by region (Langley and Hampton, 2008) with a special emphasis on migration. This demonstrated high levels of skipjack tuna migration between all provinces within the sub-region of Solomon Islands.



(a) (b)

Figure 5: Resilience index $R(B_0)$ with $\alpha = 0.6$ for configuration without FADs (a) and with FADs (b) under different combination of coral reef fish initial biomass $B_{1,2}(t_0)$ and skipjack tuna initial biomass $B_3(t_0)$ with an amplitude from 0.2 (20%) to 2 (200%), the provincial situations are depicted by their relative coral reef fish biomass as a proportion of the national multiplier unit for Choiseul (Ch.), Central (C.), Gadacanal (G.), Isalbel (I.), Makira (Mak.), Malaita (Mal.) and Western Province (W.P.)

5 Discussion

The resilience index proposed in this paper is based on a robust viability framework (Doyen and Béné, 2003). This index integrates the basic human needs that mediate households' decisions (food security and need for cash) with the minimum biomass level that ensures the sustainability of the resource, to define a multi-dimensional domain within which the whole system viability is satisfied. In this context the resilience index measures the ability of the system to stay in its viability domain within a finite period of time. Such an index provides insights into the dynamics of the system in the context of uncertainty, technical innovation, and provincial specificities. This work confirms the observations of Albert et al. (2014) and Roeger et al. (2016) on the potential of pelagic resources and the importance of technical innovations through a dynamic quantitative approach and a resilience framework.

5.1 The potential role of FADs in improving social-ecological resilience

A first important result that emerges from the analysis is that the reference (2011) situation in the Solomon Islands fisheries is not viable and that this lack of viability jeopardizes the resilience of the system. The analysis suggests in particular that the main limiting factor is the low level of cash generated by the households through selling a share of their catch. The simulations indicate that this cash barely maintains households above the poverty line. The simulations also indicate that this low level of cash is, in turn, the consequence of the degraded reef resources, leading to poor catch and income-poverty.

The system will remain only partially resilient unless some of these constraints can be relaxed. The option explored in this paper is the introduction of in-shore FADs which are expected to make the tuna resource more accessible to local small-scale fishers. The simulations show that by increasing the catchability of the tuna, the FADs allow these fishers to ease the pressure on the reef fishery. This strategy enables them to increase their cash and move away from the viability cash threshold, thus providing more resilience to the system (Fig.4). As such the implementation of FADs effectively promotes the socio-economic viability of the system (both cash and subsistence). The overall status of the resource seems also to improve, even though the skipjack tuna resource decreases slightly under the FADs scenario.

Pauly et al. (1998) propose the ratio between the biomass of all prey and all predator species to be the best indicator or reef fish community health (the higher the proportion of preys over predators, the worse the resource condition). Our model differentiates between piscivors and herbivores, and thus provides insights into the health of the reef system. Without FADs, the reduction of effort in the coral reef fishery, induced by low reef fish biomass, has a beneficial effect on prey while the predators biomass struggles to recover. With FADs, the reduced effort benefits the balance of the reef fish system with prey and predator in dynamic equilibrium.

In the context of small scale fisheries in developing countries, with high fishery dependence and universally low enforcement capacity, such reductions in effort is more likely to happen if other resources are available such as the skyjack tuna. The communities studied by Roeger et al. (2016) have illustrated how the pelagic resource could be exploited as an adaptive strategy. These communities however are close to the city of Auki which constitutes a big market to sell a part of the catch, especially a mono specific catch. According to Hardy et al. (2016), the most populated area are often the least resilient. The presence of a tuna market in a reachable city could therefore encourage the fishers to go for a pelagic resource and reduce their effort in the lagoon. Nonetheless, under tuna fishing specialization, the small-scale fishery might become more vulnerable to exogenous stock fluctuations. In terms of impacts of the industrial fishery, the model accounts already for a high variation through a calibration using industrial fleet data from 1996 to 2006. Finally, as the fishers noticed, it takes two to three weeks for the FAD to "recover" from industrial seine fishing and reach again the original fish density (personal data). As a matter of fact, the tuna resource is present all year round and it takes less that a month to come from low to sufficient stock' levels which again tends to argue for the resilience of the tuna species (Bertignac et al., 2000).

Within least populated areas, and even with the introduction of in-shore FADs and the increased focus on the tuna resource, the reef fishery will remains a critical cultural and socio-economical element in the system. Some occasional fishers will continue to fish with elementary gears and with a minimum effort of 2 hours per month, sometimes more, as the control is impossible to implement, although the subsistence driven fishery seems to discourage the 'race for fish' dynamics (Hardy et al., 2016).

To some extent these results are in line with a recent analysis completed by Hardy et al. (2013), in which the authors also conclude that the introduction of FADs in the Solomon Islands' small-scale fisheries would provide an alternative option to strengthen the viability of the system, but only under stringent conditions. These authors' analysis shows in particular that in order to remain viable in the future the Solomon Islands fisheries will not only have to introduce FADs, but also accept some initial reduction in fishing effort and a progressive increase over time in the commercialisation of the fisheries, with a larger proportion of the catch sold for cash and less retained for home-consumption. Our model suggests that the greatest increase in system resilience will be achieved if the increased yield available through the introduction of FAD is sold (rather than consumed by fisher households) to improve cash. This is because the subsistence catch is currently reasonably above its viability threshold in Fig.4, suggesting that there is some 'space for manoeuvre' (flexibility), and that indeed a larger share of the catch could be sold. The subsistence is a fundamental component of the global resilience for fishers' communities through fish distribution (Hardy, 2016). This crucial social role of fish is guarantee only if α (the percentage of catch retained by fishing households for consumption or barter) is above 40 % (Hardy et al., 2013). Since alpha is equal to 60% in this study, a small change in the alpha would prevent a poverty situation while continuing to supply all people connected to a fisher social network. Yet, Albert et al. (2014) shows how much the household and community lifestyle can be seen as threatened when more individual fishing enterprise favor cash rather than subsistence.

In sum, it seems that the FADs option, as a technical innovation, does modify the system dynamics in such a way that a resilience 'space' is created (indicated by a dark blue zone in Fig.2b compared to Fig.2a). Such result brings new insights on pelagic small scale fisheries where the resilience is provided by new fishing technique, and then strengthened by socio-economical adjustments around the subsistence use / commercialisation of the catch (Kenter et al., 2011).

While these different results are encouraging, they come with an important caveat regarding the minimum biomass of tuna. This minimum biomass could eventually become threatened if the tuna resource were to be exposed to a higher fishing pressure induced by the growth of the industrial fishery and the coastal pollution. Both elements are mentioned by locals (personal observation) but no studies have assessed exactly these factors and their detrimental effects on the stocks. Several analysis present the skypjack tuna as a relatively robust specie, largely due to a high spawning capacity (Hunter et al., 1986). However, the situation and the habitats might change rapidly in a near future. In this context, the challenge for resource managers in the Solomon Islands is therefore to reduce pollution and provide an inshore FADs' network among the coasts while at the same time look for international arrangements to secure an inshore tuna stock.

5.1.1 Provincial considerations

The disaggregation of the national data into provincial sub-analyses provides further information that has relevance from a management perspective. Our use of provinces as a spatial unity is equivalent to the approach adopted by Kronen et al. (2010) which aggregates islands with homogeneous demographics and socio-economic structure as well as comparative dependency on, and access to, reef and lagoon resources. Based on the 2011 conditions, two provinces (Guadalcanal and Malaita) are clearly in a non-resilience dynamics with or without FADs. The introduction of FADs in these two provinces does not improve the situation for fishery resources. In Malaita, the very high population ($>$ 120000 inhabitants (National Statistic Office, 2008)) puts considerable pressure on natural resources including land and fisheries. This situation is likely to have played a role in the migration of numerous Malaitans to Guadalcanal, one event that is said to have been partly responsible for the ethnic tension that occurred in 2000 (Schoorl and Friesen, 2002).The strong urban migration that occurs in Guadalcanal, is also a probable reason why this main province is far from the resilience zone. Furthermore, the seas surrounding Guadalcanal present the lowest tuna density compared to the other provinces (Langley and Hampton, 2008), which might also contribute to the poor resilience of the province.

In contrast, our model suggests that the introduction of FADs does change the status of the other provinces. Three of them (Isabel, Makira, and the Central province) which were not resilient based on the 2011 conditions become resilient once FADs are introduced. The last two provinces (Choiseul and Western Province) are the most resilient with FADs. Incidentally, these two provinces are known to be characterized by the presence of larger reef areas relative to the number of fishers, and as such their reef fisheries alone may already be more resilient. These two provinces are not isolated, however, and their economic connection with Guadalcanal is known and has been studied by Brewer et al. (2012) who reports an important reef fish exchange. At the present time, however, it is difficult to know if the skypjack tuna will replace the coral reef fish within this intra-country exports.

Yet our analysis also concurs with those of Fasey et al. (2011) in the Makira province[10] and Albert et al. (2014)[11] when it shows that the establishment of FADs, while providing some clear benefits (see above), is not a 'silver bullet' for improving small-scale fishery system production and resilience. Other alternatives as poultry development[12] will have to be proposed to assure that the three core issues of biodiversity/resource conservation, food security and poverty alleviation in the South West Pacific are resolved (LaFranchi, 1999; Shearman, 1999; Hardy et al., 2013).

6 Conclusion

Fisheries, in particular small-scale fisheries, play a critical role both in relation to poverty alleviation and food security (Béné, 2006). Yet three quarters of the world's fish stocks are estimated to be fully or over-exploited (FAO et al., 2012) and marine biodiversity is increasingly threatened in many parts of both developed and developing world's (Worm et al., 2009; Butchart et al., 2010; Cardinale et al., 2012). In this article we explored these issues in the context of the small-scale fisheries of the Solomon Islands. For Solomon Islands' communities, marine resources constitute a unique and critical pool of available protein and an important source of cash. However, like in many other places in the Pacific region, there is evidence of localized depletion of finfish in several parts of the Solomon' archipelago (Green et al., 2006; Brewer et al., 2009).

To explore these issues, we developed a bio-economic model and calibrated it using Solomon Islands' data. We were in particular interested in exploring the extent to which in-shore Fish Aggregating Devices (FADs) could increase the resilience of the fisheries system and help reconciling social, economic and ecological priorities. The underlying approach used for this builds on the viability approach as initially developed by Aubin (1991) and others.

10. Fasey et al. (2011) also address the relationship between subsistence and cash earnings through the use of marine resources with a certain emphasis on the demographic factors which tend to question the protein self-sufficiency and the local cash opportunities.

11. While Albert et al. (2014) prove the acceptability and the utility of the FADs, the authors highlight some socio-economic limitation of the FADs' implementation in a near future, mentioning impacts and tradeoffs notably on a customary perspective with subsistence and cash obligations.

12. ACIAR, 2003. Feeding village poultry in the Solomon Islands, project number LPS/2003/054 (In a case of a poultry development, the results of this project can be integrated in the same sort of stochastic biotextc-economic model trough an extra resource which interactions with the fish stocks relates to pollution effects as eutrophisation)

In addition to this viability framework, the paper uses the concept of resilience to analyse the behaviour of the system around the boundaries of its viability domain. Quantifying or measuring resilience has been so far methodologically difficult (Frankenberger and Nelson, 2013; Béné et al., 2012). In our case, we follow Béné et al. (2001) and Martin (2005) who, in a dynamic context, propose to link resilience to the concept of 'time of crisis'.

At the system/country level our analysis suggests that the introduction of in-shore FADs would improve the resilience of the fishery social-ecological system. Without FADs, the fisheries would rapidly become unviable and this lack of viability jeopardizes the resilience of the whole system. Introducing in-shore FADs would allow the small-scale fishers to redirect part of their fishing effort towards the tuna resource, thus boosting their ability to generate more cash and to maintain themselves above the poverty line. This re-allocation of the fishing effort would also release the pressure on the reef resources and improve the overall resilience and viability of the system.

The analysis was furthered through a provincial (sub-national) assessment. The provincial analysis shows that the resilience of some of the provinces would be strengthened, while in other provinces the fisheries would remain no-resilient, even after the introduction of FADs. This suggests that while the FAD implementation stands as a valuable tool to improve the resilience of fishery systems, alone they do not present a long-term solution. They must be part of a larger toolbox of technological, governance and livelihood interventions.

These various results are in line with other recent analyses (Hardy et al., 2013), in which the authors also conclude that the introduction of FADs in the Solomon Islands small-scale fisheries would provide an alternative option to strengthen the viability of the system but only under specific conditions. One of these conditions relies in the customary system of subsistence sharing which limits the cash opportunity of direct selling and participate as a socio-economic factor of resilience (Gordon, 2011; Handmer and Choong, 2009). Likewise, a recent empirical analysis of catch and social outcomes from introduction of FADs in Solomon Islands Albert et al. (2014) similarly concludes that FADs should be treated as an option for diversification in fishery systems, but stresses the potential existence of trade-offs and risks. Complementary benefits may be found in community-based coastal resource management (Andrew et al., 2007; Govan et al., 2009) but also in developing alternative sources of protein. Brewer (2011) for instance suggests to actively look for other animal sources, a strategy that the government is already exploring through some projects involving cattle and poultry investments (ACIAR, 2003).

This study is one of the first ones to address the interactions between tuna and coral fish on a multi-scale perspective, this possibility has been achieved though the use of the viability theory. Prior to its use in this Solomon Islands case-study, viability theory has been used to explore multi-objective problems in relation to natural resource management and conservation (Baumgärtner and Quaas, 2009; Pereau and Doyen, 2012; Cissé et al., 2013) or to biodiversity valuation (Bene and Doyen, 2008). This study illustrates its potential to address data poor situation. It also illustrates its relevance in the wider context of development, and in particular in relation to critical issues of poverty and food security, and highlights the extent to which these are intimately linked, in developing countries, to the conservation of natural resources.

7 Acknowledgments

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References

Albert JA, Doug B, Anne-Maree S, Simon A, Regon W, et al. (2014) The Contribution of Nearshore Fish Aggregating Devices (FADs) to Food Security and Livelihoods in Solomon Islands. PLoS ONE 9.

Allison EH (2011) Aquaculture, Fisheries, Poverty and Food Security. Tech. Rep. Working Paper 2011-65, The WorldFish Center, Penang, Malaysia.

Andrew NL, Béné C, Allison EH, Heck S, Ratner BD (2007) Diagnosis and management of small-scale fisheries in developing countries. Fish and Fisheries 8: 227–240.

Armitage D, Béné C, Charles AT, Johnson D, Allison EH (2012) The Interplay of Well-being and Resilience in Applying a Social- Ecological Perspective. Ecology and Society 17.

Aswani S (1998) Patterns of marine harvest effort in southwestern New Georgia, Solomon Islands:: resource management or optimal foraging? Ocean & Coastal Management 40: 207–235.

Aswani S (2002) Assessing the effects of changing demographic and consumption patterns on sea tenure regimes in the Roviana Lagoon, Solomon Islands. AMBIO: A Journal of the Human Environment 31: 272–284.

Aswani S (2006) Customary Sea Tenure in Oceania as a Case of Rights-based Fishery Management: Does it Work? Reviews in Fish Biology and Fisheries 15: 285–307.

Aswani S, Albert S, Sabetian A, Furusawa T (2007) Customary management as precautionary and adaptive principles for protecting coral reefs in Oceania. Coral Reefs 26: 1009–1021.

Aubin JP (1991) Viability theory. Cambridge, MA, USA: Birkhauser Boston Inc.

Aubin JP (2009) Viability Theory. Modern Birkhauser Classics.

Bahadur AV, Ibrahim M, Tanner T (2010) The resilience renaissance? Unpacking of resilience for tackling climate change and disasters. Tech. Rep. 1, IDS, Brighton.

Baumgärtner S, Quaas M (2009) Ecological-economic viability as a criterion of strong sustainability under uncertainty. Ecological Economics 68: 2008–2020.

Bell JD, Allain V, Allison EH, Andréfouët S, Andrew NL, et al. (2015) Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. Marine Policy 51: 584–591.

Bell JD, Kronen M, Vunisea A, Nash WJ, Keeble G, et al. (2009) Planning the use of fish for food security in the Pacific. Marine Policy 33: 64–76.

Bell JD, Purcell SW, Nash WJ (2008) Restoring small-scale fisheries for tropical sea cucumbers. Ocean & Coastal Management 51: 589–593.

Béné C (2006) Small-scale fisheries : assessing their contribution to rural livelihoods in developing countries. Tech. Rep. Fisheries Circular 1008, FAO Fisheries Circular.

Bene C, Doyen L (2008) Contribution values of biodiversity to ecosystem performances: A viability perspective. Ecological Economics 68: 14–23.

Béné C, Doyen L, Gabay D (2001) A viability analysis for a bio-economic model. Ecological Economics 36: 385–396.

Béné C, Friend RM (2011) Poverty in small-scale fisheries old issue, new analysis. Progress in Development Studies 11: 119–144.

Béné C, Godfrey-Wood R, Newsham A, Davies M (2012) Resilience: New utopia or new tyranny? - Reflection about the potentials and limits of the concept of resilience in relation to vulnerability reduction programmes. Tech. Rep. 405, Institute of Development Studies, Brighton.

Béné C, Macfadyen, Allison H (2007) Increasing the contribution of small-scale fishery to poverty alleviation and food security. Tech. Rep. 481, FAO, Rome.

Bertignac M, Campbell HF, Hampton J, Hand AJ (2000) Maximizing Resource Rent From the Western and Central Pacific Tuna Fisheries. Marine Resource Economics 15: 151–177.

Brewer TD (2011) Coral reef fish value chains in Solomon Islands: Market opportunities and market effects on fish stocks. Tech. rep., ARC Centre of Excellence for Coral Reef Studies, James Cook University.

Brewer TD, Cinner JE, Fisher R, Green A, Wilson SK (2012) Market access, population density and socioeconomic development explain diversity and functional group biomass of coral reef fish assemblages. Global Environmental Change 22: 399–406.

Brewer TD, Cinner JE, Green A, Pandolfi JM (2009) Thresholds and multiple scale interaction of environment, resource use, and market proximity on reef fishery resources in the Solomon Islands. Biological Conservation 142: 1797–1807.

Bruckner T, Petschel-Held G, Toth FL, Füssel HM, Helm C, et al. (1999) Climate change decision-support and the tolerable windows approach. Environmental Modeling & Assessment 4: 217–234.

Buckley TW, Miller BS (1994) Feeding habits of yellowfin tuna associated with fish aggregation device in American Samoa. Bulletin of Marine Science 55: 445–459.

Butchart SHM, Walpole M, Collen B, van Strien A, Scharlemann JPW, et al. (2010) Global Biodiversity: Indicators of Recent Declines. Science 328: 1164–1168.

Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, et al. (2012) Biodiversity loss and its impact on humanity. Nature 486: 59–67.

CIA (2001) The World Factbook.

Cissé AA, Gourguet S, Doyen L, Blanchard F, Péreau JC (2013) A bio-economic model for the ecosystem-based management of the coastal fishery in French Guiana. Environment and Development Economics 18: 245–269.

Cury P, Mullon C, Garcia SM, Shannon LJ (2005) Viability theory for an ecosystem approach to fisheries. ICES journal of Marine Science 62: 577.

Deffuant G, Gilbert N (2011) Viability and Resilience of Complex Systems, Concepts, Methods and Case Studies from Ecology and Society. Boston/Dordrecht/London: Kluwer Academic Publishers.

Dept I (2014) Solomon Islands: Staff Report for the 2013 Article IV consultation and Second Review Under the Extended Credit Facility Arrangement and Request for Modification of Performance Criterion. IMF Staff Country Reports, International Monetary Fund.

Désurmont A, Chapman L (2000) The use of anchored FADs in the area served by the Secretariat of the Pacific Community (SPC): regional synthesis. Tech. rep., Secretariat of the Pacific Community, Noumea, New Caledonia.

Doyen L, Béné C (2003) Sustainability of fisheries through marine reserves: a robust modeling analysis. Journal of Environmental Management 69: 1–13.

Doyen L, DeLara M (2010) Stochastic viability and dynamic programming. Systems and Control Letters 59: 629–634.

Doyen L, DeLara M, Ferraris J, Pelletier D (2007) Sustainability of exploited marine ecosystems through protected areas: A viability model and a coral reef case study. Ecological Modelling 2008: 353–366.

Doyen L, Saint-Pierre P (1997) Scale of Viability and Minimal Time of Crisis. Set-Valued Analysis 5: 227–246.

Duer-Balkind M, Jacobs KR, Güneralp B, Basurto X (2013) Resilience, social-ecological rules, and environmental variability in a two-species artisanal fishery. Ecology and Society 18: 50.

Eisenack K, Scheffran J, Kropp JP (2006) Viability analysis of management frameworks for fisheries. Environmental Modeling and Assessment 11: 69–79.

FAO (1981) Preparation and use of food-based dietary guidelines. Tech. Rep. 880, FAO, Rome.

FAO (2012) The state of World fisheries and aquaculture 2012. Tech. rep., FAO, Rome.

FAO, FIDA, PMA (2012) L'état de l'insécurité alimentaire dans le monde 2012. La croissance économique est nécessaire mais elle n'est pas suffisante pour accélérer la réduction de la faim et de la malnutrition. Tech. rep., FAO.

Fernandez E, Allain V (2011) Importance des proies récifales dans l'alimentation des thons et des grands pélagiques dans le Pacifique centre-ouest. Lettre d'information sur les pêches de la CPS 133.

Foale S (1998) Assessment and management of the trochus fishery at West Nggela, Solomon Islands: An interdisciplinary approach. Ocean & Coastal Management 40: 187–205.

Foale S (2008) Appraising the resilience of trochus and other nearshore artisanal fisheries in the Western Pacific. Traditional Marine Resource Management and Knowledge Information Bulletin 14: 12–15.

Frankenberger T, Nelson S (2013) Background Paper for the Expert Consultation on Resilience Measurement for Food Security. Tech. rep., TANGO International.

Garcia SM, Grainger JR (2005) Gloom and Doom? The future of marine capture fisheries. Phil Trans R Soc B 360: 21–46.

Gordon LN (2011) The Wantok System as a Socio-economic and Political Network in Melanesia. OMNES: The Journal of Multicultural Society 2: 31–35.

Govan H, Schwarz AM, Boso D (2009) Towards Integrated Island Management: Lessons from Lau, Malaita for the implementation of a national approach to resource management in Solomon Islands. Tech. rep., WorldFish Center Report to SPREP.

Green A, Lokani P, Atu W, Ramohia P, Thomas P, et al. (2006) Solomon Islands Marine Assessment: Technical report of survey conducted May 13 to June 17, 2004. Tech. Rep. 106, TNC Pacific Island Countries.

Hall SJ, Hilborn R, Andrew NL, Allison EH (2013) Innovations in capture fisheries are an imperative for nutrition security in the developing world. PNAS 110: 8393–8398.

Handmer J, Choong W (2009) Resilience: wantoks, transnational traders and global politics, pp. 208–219. Damien grenfell and paul james ed., London, UK: Routledge.

Hardy PY, Béné C, Doyen L, Pereau J, Mills D (2016) Viability and resilience of small-scale fisheries through cooperative arrangements. Environment and Development Economics 21: 713–741.

Hardy PY, Béné C, Doyen L, Schwarz AM (2013) Food security versus environment conservation: A case study of solomon islands' small-scale fisheries. Environmental Development 8: 38–56.

Heck S, C B, Reyes-Gaskin R (2007) Investing in African fisheries: building links to the Millennium Development Goals. Fish and Fisheries 8: 211–226.

High Level Panel of Experts (2014) Sustainable fisheries and aquaculture for food security and nutrition. A report by the high level panel of experts on food security and nutrition of the committee on world food security. Tech. rep., FAO.

Holling CS (1973) Resilience and stability of ecological systems. Annual review of ecology and systematics 4: 1–23.

Hunter JR, Macewicz BJ, Sibert JR (1986) The spawning frequency of skipjack tuna, *Katsuwonus pelamis*, from the south Pacific. Fishery Bulletin 84: 895–903.

Kawarazuka N, Béné C (2010) Linking small-scale fisheries and aquaculture to household nutritional security: an overview. Food Security 2: 343–357.

Kenter JO, Hyde T, Christie M, Fazey I (2011) The importance of deliberation in valuing ecosystem services in developing countries: Evidence from the Solomon Islands. Global Environmental Change 21: 505–521.

Kile N (2000) Solomon Islands marine resources overview. Pacific Economic Bulletin 15: 143–147.

Kinch J (2004) The Status of Commercial Invertebrates and other Marine Resources in the North-west Santa Isabel Province, the Solomon Islands. Tech. rep., United Nation Development Program.

Kronen M (2007) Monetary and non-monetary values of small-scale fisheries in Pacific Island countries. SPC Women in Fisheries Information Bulletin 16: 12.

Kronen M, Magron F, McArdle D, Vunisea A (2010) Reef finfishing pressure risk model for Pacific Island countries and territories. Fisheries Research 101: 1–10.

LaFranchi C (1999) Islands Adrift? Comparing Industrial and Small-Scale Economic Options for Marovo Lagoon Region of the Solomon Islands. Tech. rep., GreenPeace, Suva, Fiji.

Langley A, Hampton J (2008) Stock assessment of skypjack tuna in the western and central pacific ocean. Tech. rep., Oceanic Fisheries Programme, Secretariat of the Pacific Community, New Caledonia.

Larkin PA, Gazby W (1982) Theory and Management of Tropical Fisheries: Proceedings of the ICLARM/CSIRO Workshop. Manila, Philippines: D. Pauly and G. I. Murphy.

Lehodey P, Chai F, Hampton J (2003) Modelling climate-related variability of tuna populations from a coupled ocean-biogeochemical-populations dynamics model. Fisheries Oceanography 12: 483–494.

Manyena B (2006) The concept of resilience revisited. Disasters 30.

Martin S (2005) La Résilience dans les Modèles de Systèmes Ecologiques et Sociaux. Ph.D. thesis, Ecole Normale Superieure de Cachan.

Martinet V, Doyen L (2007) Sustainability of an economy with an exhausible resource: a viable control approach. Resource and Energy Economics 29: 17–39.

Mills D, Westlund L, de Graaf G, Willmann R, Kura Y, et al. (2011) Underreported and undervalued: Small-scale fisheries in the developing world, pp. 1–15. CABI.

Morris WF, Doak DF (2002) Quantitative conservation biology: the theory and practice of population viability analysis. Sinauer Associates Sunderland, Massachusetts, USA.

National Statistic Office (1999) Census Cross - Tabulations. Tech. rep., Solomon Islands Government, pacifiweb.org.

National Statistic Office (2008) Solomon Islands projected population by province 1999-2014. Tech. rep., Solomon Islands Government.

National Statistics Office, UNDP, Pacific Center (2008) Analysis of the 2005/2006 Households Income and Expenditure Survey. Tech. rep., UNDP Pacific Center.

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres F (1998) Fishing Down Marine Food Webs. Science 6 279: 860–863.

Pereau JC, Doyen L (2012) Sustainable coalitions in the commons. Mathematical Social Sciences 63: 57–64.

Prange J (2009) Nearshore fish aggregating devices: A means of habitat protection and food security in post-disaster Solomon Islands. Fisheries newsletter 130.

Ramofafia C (2004) The sea cucumber fisheries in Solomon Islands: benefits and importance to coastal communities. Tech. rep., WorldFish Center, Nusa Tupe Field Station, Western Province, the Solomon Islands.

Roeger J, Foale S, Sheaves M (2016) When 'fishing down the food chain' results in improved food security: Evidence from a small pelagic fishery in Solomon Islands. Fisheries Research 174: 250–259.

Sabetian A (2003) The association of physical and environmental factors with abundance and distribution patterns of groupers around Kolombangara Island, Solomon Islands. Environmental Biology of Fishes 68: 93–99.

Sabetian A, Foale S (2006) Evolution of the artisanal fisher: Case studies from Solomon Islands and Papua New Guinea. Traditional Marine Resource Management and Knowledge Information Bulletin 20: 3–10.

Schaefer MB (1957) Some considerations of population dynamics and economics in relation to the management of marine fishes. Journal of the Fisheries Research Board of Canada 14: 669–81.

Schoorl J, Friesen W (2002) Migration and displacement., chap. 5. Government Printe.

Schwarz A, Béné C, Bennett G, Boso D, Hilly Z, et al. (2010) Vulnerability and resilience of remote rural communities to shocks and global changes: empirical analysis from Solomon Islands. Global Environmental Change 21: 1128–1140.

Schwarz AM, Ramofafia C, Bennett G, Notere D, Tewfik A, et al. (2007) After the earthquake: An assessment of the impact of the earthquake and tsunami on fisheries-related livelihoods in coastal communities of Western Province, Solomon Islands. Tech. rep., WorldFish Center, World Wide Fund, Gizo, Solomon Islands.

Shapiro A, Dentcheva D, Ruszczynski A (2009) Lectures on Stochastic Programming. Society for Industrial and Applied Mathematics, 446 pp.

Shearman P (1999) Development options study, Marovo Lagoon, Solomon Islands: balancing the needs of Marovo and the prosperity of the nation. Tech. rep., World Wide Fund for Nature, Gizo, the Solomon Islands.

Spalding MD, Ravilious C, Green EP (2001) World Atlas of Coral Reefs. Berkeley: Univ. California Press.

Species Survival Commission, UICN (2000) IUCN Red List Categories and Criteria. Tech. rep., IUCN Council, Gland, Switzerland.

Sulu R, Hay C, Ramohia P, Lam M (2000) The status of Solomon Islands' coral reefs. Tech. rep., Global Coral Reef Monitoring Network, Townsville, Queensland, Australia.

Volterra V, Brelot M (1931) Théorie mathématique de la lutte pour la vie. Paris: Éditions Gauthier-Villars.

Worm B, Hilborn R, Baum JK, Branch TA, Collie JS, et al. (2009) Rebuilding Global Fisheries. Science 325: 578–585.

Yari M (2003/04) Beyond "Subsidence Affluence": Poverty in Pacific Island Countries. Bulletin on Asia-Pacific Perspectives .

Model's parameters

Name		Reef Predator	Reef Prey	Tuna	Reference
$B_i(2011)$	Initial Biomass	0.0033	0.1972	0.00002	(Green et al., 2006)
K_i	Carring Capacity	-	-	0.0001	(Bell et al., 2008)
B_{eq}	Equilibrium Biomass	0.0067	0.39	-	(Green et al., 2006)
W_i	Weight	0.56	0.26	11	(Green et al., 2006)
Vol_i	Diet	0.35	0	-	Fishbase
$S_{i,1}$	Trophic Interaction	- 0.111	0.007	0	(Doyen et al., 2007)
$S_{i,2}$	Trophic Interaction	- 0.127	0	0	
$S_{i,3}$	Trophic Interaction	0	0	- 98.122	
p_i	Price	5.5	4.5	5	(Kinch, 2004)

Name		Coral Fish	Tuna	Reference
l_k	Fishers population	79625	79625	(National Statistic Office, 1999)
$q_{1,k}$ $(*10^{-8})$	Catchability	3	0	
$q_{2,k}$ $(*10^{-8})$	Catchability	0.4	0	
$q_{3,k}$ $(*10^{-8})$	Catchability	0	0.3	
area_k $(*10^{10})$	Area	0.0575	2721.008	(Hardy et al., 2013)

Table 3: Compilation of the economical parameters to be integrated in equation (1) and (2) of the model

Model's construction

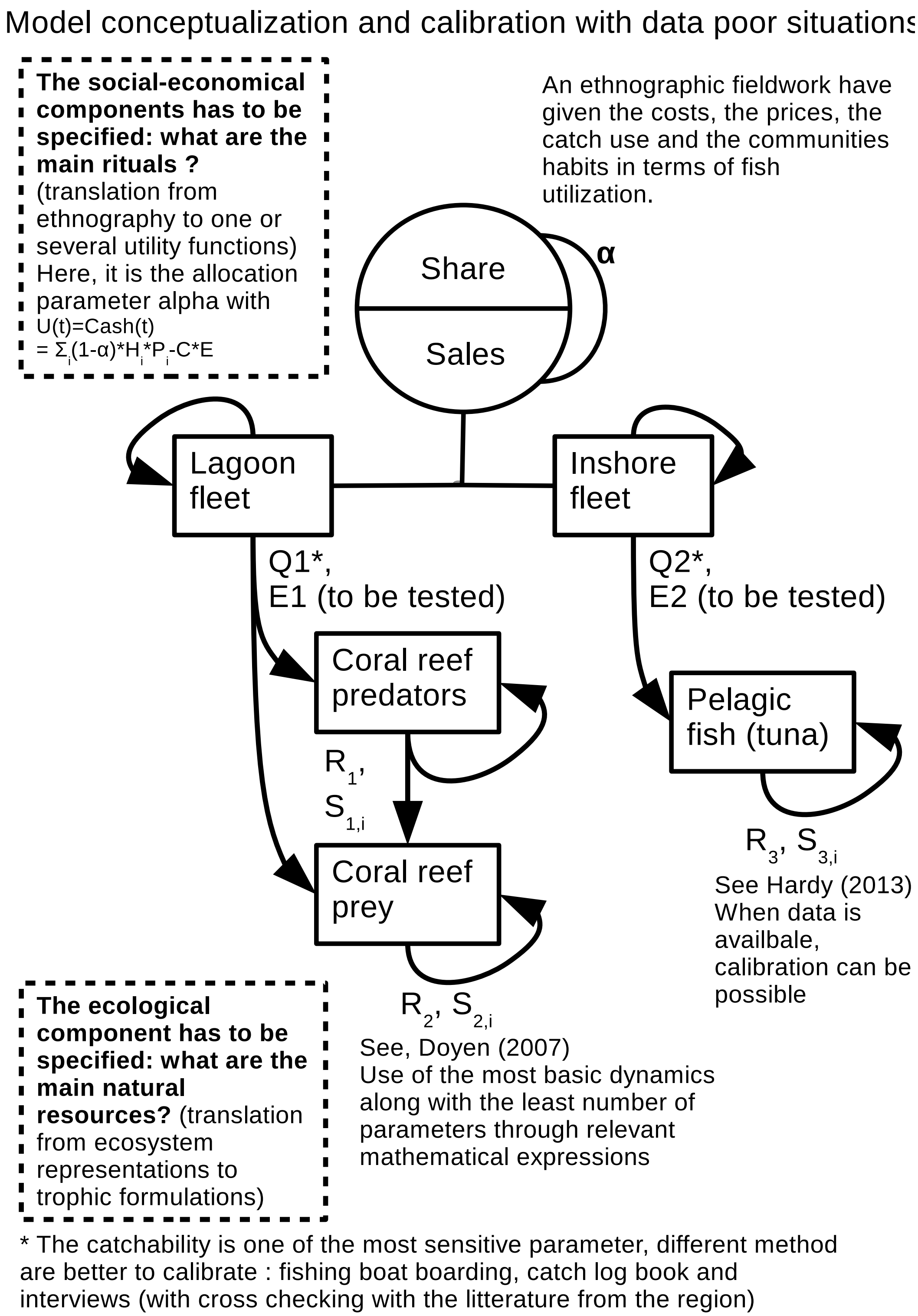

Figure 6: A conceptual map of the model building in a typical data poor situation